Spin Tilts in the Double Pulsar Reveal Supernova Spin Angular-Momentum Production

Will M. Farr

and

Kyle Kremer

Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA)
Department of Physics and Astronomy
Northwestern University, 2145 Sheridan Road, Evanston, IL 60208

w-farr@northwestern.edu, kylekremer2012@u.northwestern.edu

and

Maxim Lyutikov

Physics Department, Purdue University
525 Northwestern Avenue, West Lafayette, IN 47907

lyutikov@purdue.edu

and

Vassiliki Kalogera

Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA)
Department of Physics and Astronomy
Northwestern University, 2145 Sheridan Road, Evanston, IL 60208

vicky@northwestern.edu

ABSTRACT

The system PSR J0737-3039 is the only binary pulsar known to consist of two radio pulsars (PSR J0737-3039 A and PSR J0737-3039 B). This unique configuration allows measurements of spin orientation for both pulsars: pulsar A's spin is tilted from the orbital angular momentum by *no more than* 14 degrees at 95% confidence; pulsar B's by 130 ± 1 degrees at 99.7% confidence. This spin-spin misalignment requires that the origin of most of B's present-day spin is connected to the supernova that formed pulsar B. Under the simplified assumption of a single, instantaneous kick during the supernova, the spin could be thought of as originating from the off-center nature of the kick, causing pulsar B to tumble to its misaligned state. With this assumption, and

using current constraints on the kick magnitude, we find that pulsar B's instantaneous kick must have been displaced from the center of mass of the exploding star by at least 1 km and probably 5–10 km. Regardless of the details of the kick mechanism and the process that produced pulsar B's current spin, the measured spin-spin misalignment in the double pulsar system provides an empirical, direct constraint on the angular momentum production in this supernova. This constraint can be used to guide core-collapse simulations and the quest for understanding the spins and kicks of compact objects.

Subject headings: pulsars: individual (J0737-3039) — supernovae: general

1. Introduction

The radio-pulsar system PSR J0737-3039 is the only binary pulsar known to consist of two radio pulsars: PSR J0737-3039 A (Burgay et al. 2003) and PSR J0737-3039 B (Lyne et al. 2004). Table 1 gives the parameters of this system. This unique configuration has permitted measurements of spin orientation for both pulsars (Ferdman et al. 2008; Lyutikov & Thompson 2005; Breton et al. 2008): pulsar A's spin is tilted from the orbital angular momentum vector by *no more than* 14 degrees at 95% confidence (Ferdman et al. 2008); pulsar B's by $130.0^{+1.4}_{-1.2}$ degrees at 99.7% confidence. Here we argue that this large difference between the two pulsar spin tilts requires that the origin of most of B's spin is connected to its supernova (SN) explosion; the spin of B's progenitor, expected to be aligned with the pre-SN orbit due to tidal interactions, cannot be invoked to explain the present-day misaligned spin of pulsar B. PSR J0737-3039 B is currently believed to have formed from an electron-capture supernova triggered in a massive O-Ne-Mg white dwarf (van den Heuvel 2004; Willems & Kalogera 2004; Piran & Shaviv 2005; Stairs et al. 2006; Wang et al. 2006; Willems et al. 2006; van den Heuvel 2007; Breton et al. 2008; Wong et al. 2010). Our results demonstrate that, whatever the details of its formation mechanism, the supernova that formed PSR J0737-3039 B produced the majority of its current spin. If the source of the present-day spin of pulsar B is a single, impulsive kick, then this kick must be off-center so that it tumbles the pulsar to its current orientation. Using constraints on the SN kick magnitude derived from the orbital and kinematic parameters of the system (Wong et al. 2010) we find that this kick must have been displaced from the center of mass of the exploding star by at least 1 km and probably 5–10 km. Such offset distances are a significant fraction of the expected radii of neutron stars. Off-center kicks were first suggested in Spruit & Phinney (1998) on purely theoretical grounds.

2. Evolutionary History

PSR J0737-3039 likely evolved from two stars originally massive enough to undergo supernova (SN) explosions and form two neutron stars (Tauris & van den Heuvel 2006) at the end of their

nuclear lifetimes. Given the measured spin magnitudes and inferred magnetic fields (Burgay et al. 2003; Lyne et al. 2004; Ferdman et al. 2008; Lyutikov & Thompson 2005; Breton et al. 2008), pulsar A was the first-born neutron star, while pulsar B formed in a second SN. After the first SN the system passed through a high-mass X-ray binary phase. In this phase, pulsar A accreted matter from its companion, leading to some spin-up. Eventually, pulsar A's companion evolved off the main sequence and its expanding hydrogen envelope enveloped pulsar A. In this common-envelope phase, tidal interactions between the stars circularized the orbit and are expected to have aligned the spins of pulsar A and of pulsar B's progenitor with the orbital angular momentum axis (perpendicular to the orbital plane). The transfer of orbital kinetic energy to the envelope eventually removed the outer layers of pulsar B's progenitor, leaving pulsar A in a tight orbit with the exposed helium-rich core of B's progenitor. After another brief period of mass transfer onto pulsar A (Dewi & van den Heuvel 2004; Willems & Kalogera 2004), the helium star exploded in the second SN, forming pulsar B. As a result of the multiple mass-transfer phases between the two SN events, just before pulsar B's SN the system was in a close, circular orbit with *both stars' spins aligned with the orbital angular momentum vector.*

Due to asymmetries associated with the SN ejecta (matter and/or neutrinos) SNe are thought capable of imparting a significant recoil impulse, a "kick", to any remnant surviving the explosion (see, e.g., Janka et al. (2008) and references therein). When a SN occurs in a binary system, these kicks can significantly alter the orbital parameters or even disrupt the binary. The kick component directed parallel to the pre-SN orbital plane causes a change in the eccentricity and semi-major axis of the orbit; the component perpendicular to the pre-SN orbital plane can also cause a change in the inclination of the orbital plane. In the PSR J0737-3039 system, pulsar A's small spin-tilt angle (less than 14 degrees at 95% confidence using a two-pole emission model (Burgay et al. 2003; Lyne et al. 2004; Ferdman et al. 2008)) is indicative of a relatively small out-of-plane kick from the SN that formed pulsar B (Wong et al. 2010). Pulsar A's spin-orbit misalignment occurs only because the orbital plane is tilted by the SN kick, while pulsar A's spin remains fixed in the inertial frame aligned with the pre-SN orbital angular momentum axis (Figure 1). Such a spin tilt for pulsar A occurs independently of the effects of the second SN on pulsar B's spin. In other words, the observed tilt of pulsar A's spin by itself does not require any change in the spin angular momentum of pulsar B relative to its progenitor. However, unless the SN contributes significant amounts of angular momentum to the nascent pulsar, the orientation of pulsar B's spin will be the same as its progenitor's spin, i.e. aligned with the pre-SN orbital plane and pulsar A's spin. Surprisingly, pulsar B's spin is in fact retrograde: tilted by $130.0^{+1.4}_{-1.2}$ degrees (99.7% confidence; Ferdman et al. 2008) relative to the current orbital angular momentum vector (see Figure 1)!

3. The Need for Spin Angular Momentum from the Supernova

To produce pulsar B's retrograde spin, the SN must have significantly torqued pulsar B, causing it to tumble to the currently observed spin-orbit orientation. The pre-SN spin, $\mathbf{S}_0$, the angular

momentum produced by the SN ejecta, $\Delta\mathbf{S}$, and the post-SN spin[1], $\mathbf{S}_{SN}$, are related by the conservation of angular momentum

$$\mathbf{S}_{SN} = \mathbf{S}_0 + \Delta\mathbf{S}. \tag{1}$$

To determine $\Delta\mathbf{S}$, we must know $\mathbf{S}_0$ and $\mathbf{S}_{SN}$, but we only know the direction, not the magnitude, of $\mathbf{S}_0$ and the relationship between $\mathbf{S}_{SN}$ and the spin measured today is complicated by relativistic precession (Breton et al. 2008). However, we can still place constraints on $\Delta\mathbf{S}$. Relativistic precession causes the individual pulsar spins to precess about the total angular momentum of the system, which is approximately parallel to the orbital angular momentum. Such precession preserves the angle between the total angular momentum and the spin (which is the spin colatitude), but not the azimuthal orientation. Thus, the colatitude of $\mathbf{S}_{SN}$ relative to the normal to the current orbital plane is equal to the colatitude of the current spin—130 degrees. Based on the spin of pulsar A, the current orbital plane could be tilted at most 14 degrees relative to the pre-SN orbital plane. Therefore the colatitude of $\mathbf{S}_{SN}$ relative to the pre-SN orbital plane—and therefore relative to $\mathbf{S}_0$—is at least 116 degrees. This is also the minimum angle between $\mathbf{S}_0$ and $\boldsymbol{\Delta}\mathbf{S}$. The angular momentum produced by the SN must be *significantly* mis-aligned with the progenitor spin. To date, most SN simulations have focused on non-rotating progenitors (for example, see Blondin & Mezzacappa 2007; Rantsiou et al. 2011; Wongwathanarat et al. 2010); it remains to be seen whether the spin produced by the SN from the collapse of a *rotating* progenitor can be so significantly mis-aligned with the progenitor's rotation axis.

The typical moment of inertia (Spruit & Phinney 1998) of a neutron star is $0.36MR^2$; using pulsar B's measured mass of $1.25M_\odot$ (see Table 1) and a radius of 10 km, its current spin angular momentum is 2×10^{45} g cm^2 s^{-1}. Since this spin is retrograde whereas the pre-SN spin is roughly aligned (within 14°, given pulsar A's small spin tilt) with the current orbital plane, we can place a lower limit on the change of angular momentum needed to explain pulsar B's large and retrograde spin tilt,

$$\Delta S \geq 2 \times 10^{45}\,\mathrm{g\ cm^2\ s^{-1}}, \tag{2}$$

where equality holds when $S_0 = 0$. Because the angle between $\mathbf{S}_0$ and $\mathbf{S}_{SN}$ is greater than 90 degrees, any progenitor spin only increases the amount of angular momentum that must be added to the pulsar by the kick. This is demonstrated geometrically in Figure 2c.

The above discussion has been fully general. To extract more constraints from the observed spin-spin misalignment, we must make some assumptions about the origin of the pulsar spin. As a simplified model to elucidate the scales involved in this scenario, let us assume that the same impulsive kick (i.e. linear momentum) that changes the orbit of the system is also offset from the center of mass of pulsar B, and therefore applies a torque sufficient to produce the observed spin

[1]It is important to distinguish between pulsar B's spin vector right after the supernova and its present-day spin vector because relativistic effects cause the spin vector to precess about the total angular momentum (Breton et al. 2008), leading to a time-varying azimuthal component.

angular momentum. The kick and offset vectors must lie in the plane perpendicular to $\Delta\mathbf{S}$ (see Equation 3). The kick velocity, $\mathbf{v}_K$, the offset vector relative to the center of mass, $\mathbf{r}$, and the change in B's spin vector are related by

$$\Delta\mathbf{S} = \mathbf{r} \times \Delta\mathbf{p} = \mathbf{r} \times M_B\mathbf{v}_K, \tag{3}$$

where $\Delta\mathbf{p} = M_B\mathbf{v}_K$ is the change in linear momentum induced by a change in velocity of $\mathbf{v}_K$ in an object with mass M_B. The offset length r and kick velocity magnitude v_K must then satisfy the inequality

$$r \geq \frac{\Delta S}{M_B v_K}, \tag{4}$$

where $\Delta\mathbf{S}$ is the magnitude of the change of B's spin; the equality holds only when the kick and offset are perpendicular to each other.

The relative orientation of the current spin provides a constraint on the kick direction in this scenario. Let the colatitude of $\Delta\mathbf{S}$ relative to the pre-SN orbital plane be θ_Δ; because the angle between $\mathbf{S}_0$ and $\mathbf{S}_{SN}$ is greater than 90 degrees, no matter the magnitude of $\mathbf{S}_0$ we must have $\theta_\Delta \geq 116$ degrees. Let the plane perpendicular to $\Delta\mathbf{S}$ make an angle ψ with respect to the pre-SN orbital plane. Then we have $\psi = 180 - \theta_\Delta \leq 64$ degrees. The kick, $\mathbf{v}_K$, lies in this plane and therefore must have colatitude θ_K that satisfies

$$90 - \psi = 26 \leq \theta_K \leq 154 = 90 + \psi \tag{5}$$

This geometry is illustrated in Figure 2. The constraint in Equation 5 is consistent with the constraint on kick colatitude in Figure 7 of (Wong et al. 2010), but tighter.

The constraint on the magnitude of the spin change, Equation (2), together with Equation (4), imply a lower limit on the offset distance

$$r \geq 3.2 \left(\frac{25\text{km s}^{-1}}{v_K}\right) \text{km}. \tag{6}$$

If we assume that the core of pulsar B's progenitor was in synchronous, rigid-body rotation just before the supernova then $S_0^{SR} \simeq 2 \times 10^{45}\,\text{g}\,\text{cm}^2\,\text{s}^{-1}$, and the limit on the offset distance rises by a factor of 1.8:

$$r_{SR} \geq 5.8 \left(\frac{25\text{km s}^{-1}}{v_K}\right) \text{km}. \tag{7}$$

Wong et al. (2010) used the measured semi-major axis, eccentricity and proper motion of the J0737-3039 system (see Table 1) to constrain the kick imparted to the system by the second SN. The Wong et al. (2010) analysis assumed that the pre-SN orbit was circular and that the system came from a progenitor population with number density

$$n(R, z) = n_0 \exp\left(-\frac{R}{h_R}\right) \exp\left(-\frac{|z|}{h_z}\right), \tag{8}$$

with $h_R = 2.8$ kpc and $h_z = 0.07$ kpc the galactic scale length and height, respectively, moving with the local galactic rotation velocity. The SN kick and mass loss must then induce the current eccentricity and semi-major axis in the orbit and give the system as a whole a velocity such that it moves in the galactic potential to its current location in the 100 to 200 Myr since the second SN (Lorimer et al. 2007). Because of the uncertainty in the amount of mass loss, pre-SN semi-major axis, pre-SN galactic location, the age of the system, and the measurement uncertainty in the current orbital parameters, a range of kick magnitudes between 0 and 60 km/s is allowed in the Wong et al. (2010) analysis (Wong et al. 2010, Figure 5). In Figure 3 we show the probability distribution of minimum offset distances implied by this distribution of kick velocities. Even for large kick velocities, the minimum offset distance exceeds ~ 1 km. For the smallest allowed kicks, the minimum offset distances exceed the current ~ 10 km radius of the neutron star.

The magnitude of the offset, r, required to produce the needed ΔS depends on the relative orientation of the offset and kick, $\mathbf{v}_K$. If the angle between $\mathbf{r}$ and $\mathbf{v}_K$ in the plane perpendicular to $\mathbf{\Delta S}$ is θ_{rK}, then

$$r = \frac{\Delta S}{M_B v_K \sin\theta_{rK}}, \tag{9}$$

which is larger than the minimum offset distance by a factor of $(\sin\theta_{rK})^{-1}$ (see Equation 3). Kicks that are nearly aligned with the radial vector (small θ_{rK}) require arbitrarily large off-center distances to match the current spin orientation. Even modest misalignments of 40 degrees give an enhancement factor of $\sin^{-1} 40 \sim 1.6$ over the offset for perpendicular $\mathbf{r}$ and $\mathbf{v}_K$.

4. Discussion

Multi-dimensional simulations (Blondin & Mezzacappa 2007) of core-collapse SNe have shown that an instability in a stationary accretion shock (SASI) may provide a method of depositing a substantial amount of spin angular momentum (2×10^{47} g cm^2 s^{-1}) onto a proto-neutron star as part of the collapse process itself and separate from any rotation of the progenitor. (In fact, the simulations of Blondin & Mezzacappa (2007) used non-rotating progenitors.) This would be more than enough angular momentum to account for the observed spin angular momentum of pulsar B (2×10^{45} g cm^2 s^{-1}). The general consensus from recent evolutionary studies (van den Heuvel 2004; Willems & Kalogera 2004; Podsiadlowski et al. 2005; Stairs et al. 2006; Wang et al. 2006; Willems et al. 2006; van den Heuvel 2007; Breton et al. 2008; Wong et al. 2010) is that pulsar B was formed in an electron-capture SN, where an iron core is never formed and instead core collapse is initiated through electron captures onto Ne/Mg nuclei (Dessart et al. 2006; Kitaura et al. 2006; Podsiadlowski et al. 2004; Miyaji et al. 1980; Nomoto 1984, 1987). During the course of such a collapse, the proto-neutron star shrinks from a radius of ~ 100 km to ~ 10 km.

We emphasize that the assumption of the foregoing discussion that the kick is applied at a single location is simplistic (see, e.g., Spruit & Phinney (1998)); in a real supernova, both linear and angular momentum will be accumulated by the proto-neutron star throughout its formation

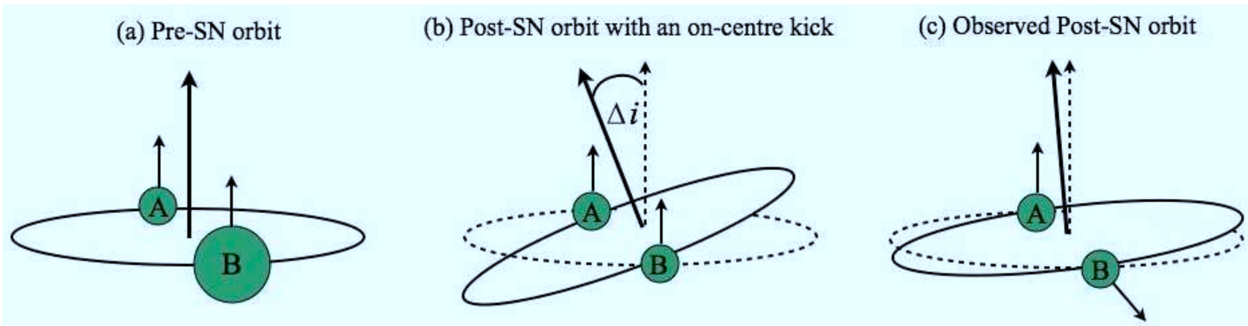

Fig. 1.— Effect of SN kick on binary orbit. The pre-SN orbit containing pulsar A and pulsar B's progenitor is shown in (a). The effect of an on-center SN kick that slightly changes the inclination of the orbit is illustrated in (b). Notice the post-SN alignment of the two pulsars' spin axes. Part (c) illustrates the present-day orbit with a 130 degree misalignment between pulsar B's spin axis and the orbital axis.

Table 1: J07373-3039 System Parameters. Except as noted, properties are given in Burgay et al. (2003); Lyne et al. (2004).

Distance	600 pc
Galactic Latitude	245.2 deg
Proper Motion	10 km/s
Spin Period (A)	22.7 ms
Spin Period (B)	2.8 s
Mass (A)	1.34 $M_\odot$
Mass (B)	1.25 $M_\odot$
Spin-orbit misalignment (A)	$\leq$ 14 deg (95% confidence) (Ferdman et al. 2008)
Spin-orbit misalignment (B)	$130.0^{+1.4}_{-1.2}$ deg (99.7% confidence) (Lyutikov & Thompson 2005; Breton et al. 2008)
Orbital Period	2.4 hrs
Semi-major Axis	1.26 $R_\odot$
Eccentricity	0.0878

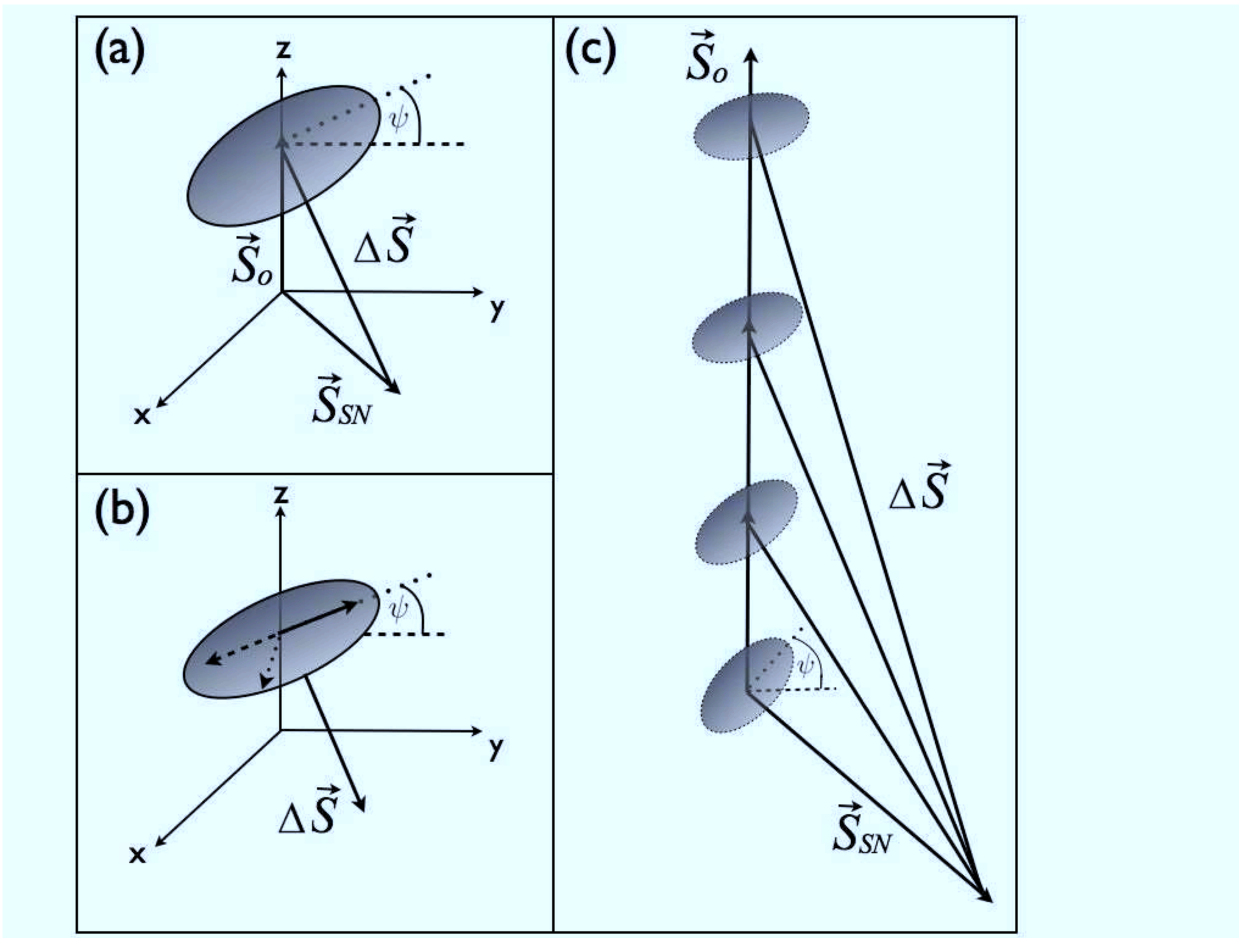

Fig. 2.— Geometry of the angular momentum change due to an off-center kick imparted to the nascent pulsar. The x-y-z reference frame is anchored on pulsar B at the time of its SN; the x-y plane is the pre-SN orbital plane. In panel (a) we show the relationship between $\mathbf{S}_0$, $\mathbf{S}_{SN}$, and $\Delta\mathbf{S}$ and the orientation of the plane orthogonal to $\Delta\mathbf{S}$ (which is inclined by an angle ψ with respect to the orbital plane). In panel (b) we show that vectors lying in the plane orthogonal to $\Delta\mathbf{S}$—like $\mathbf{v}_K$—can have an inclination with respect to the orbital plane that varies between $-\psi$ and ψ, leading to the constraint on the colatitude of $\mathbf{v}_K$ of $90-\psi \leq \theta_K \leq 90+\psi$ found in Equation (5). In panel (c) we show that as the magnitude of $\mathbf{S}_0$ increases, $\Delta\mathbf{S}$ increases in magnitude (see Equation (2)) and tilts toward the south pole, reducing ψ. Therefore, the most conservative constraints on θ_K are obtained when $S_0 = 0$, giving $26 \leq \theta_K \leq 154$ as in Equation (5).

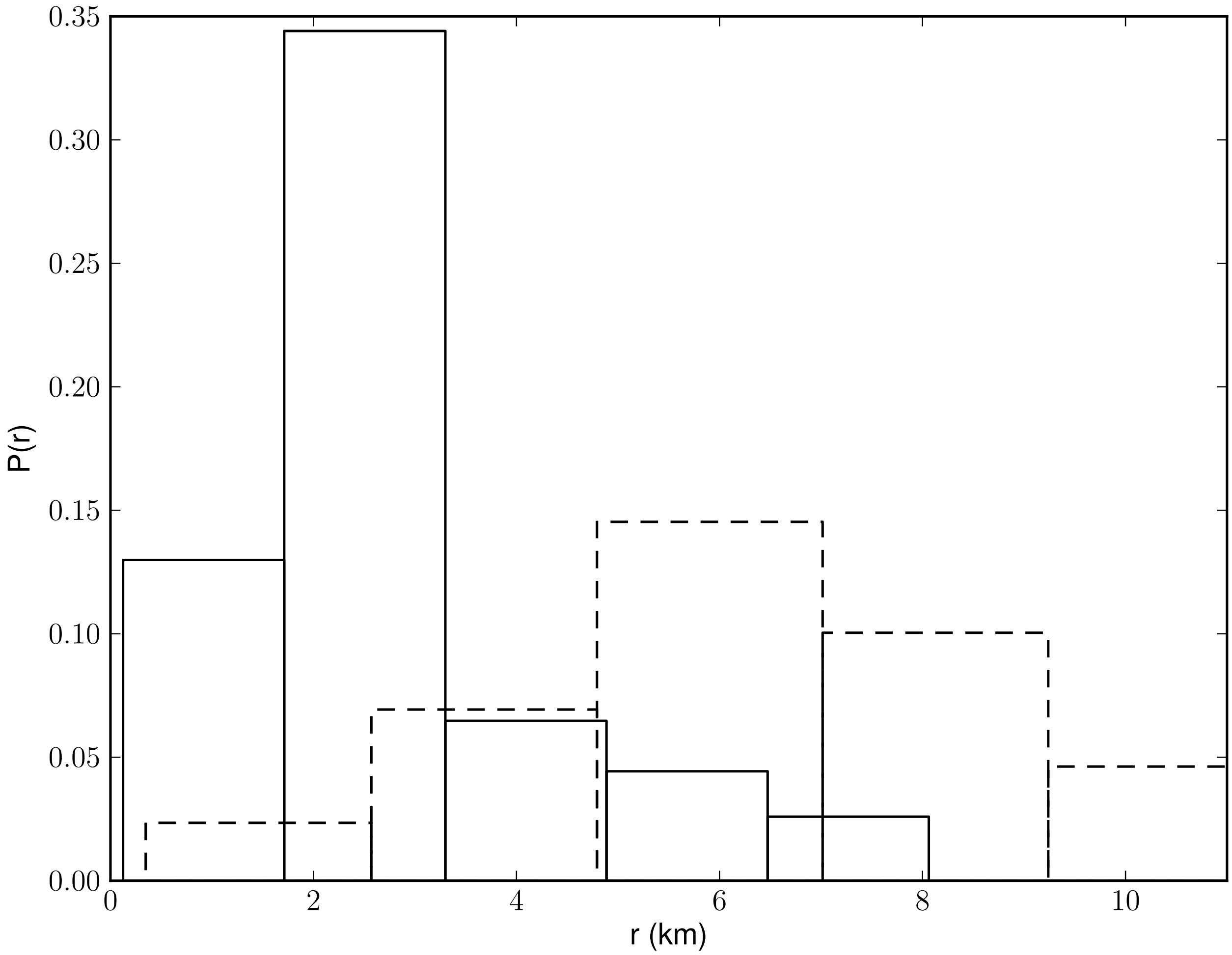

Fig. 3.— Distributions of minimum offset distances implied by the current orbital constraints (Wong et al. 2010) on kick magnitudes (see Equation (6)). The solid line gives the distribution assuming that $S_0 = 0$, with a kick that is orthogonal to the offset vector. The dashed line assumes that the core of pulsar B's progenitor was in synchronous, rigid-body rotation just prior to the supernova ($S_0 = S_0^{SR} \simeq 2 \times 10^{45}\,\mathrm{g\,cm^2\,s^{-1}}$) and that the kick-offset angle is 40 degrees.

at many different locations. In this more realistic context, the constraints above on offset distances should be interpreted instead as constraints on the offset scale at which the *bulk* of the linear and angular momentum is accumulated. More precise constraints will require detailed modeling of the hydrodynamic process of momentum accumulation in the supernova that formed PSR J0737-3039B. Nevertheless, it is interesting that the location of kicks inferred from such a simple model is consistent with kick origins in the bulk of the shrinking proto-neutron star during the supernova (see Figure 3). Some recent SN modeling suggests that the processes that produce the kick and those that impart rotation to the resulting neutron star produce independent kicks and spins, and therefore there is little correlation between the kick magnitude and direction and the rotation imparted to the post-SN compact object (Wongwathanarat et al. 2010; Rantsiou et al. 2011). In this case the offset length scale inferred above from the dynamical constraints on the kick would not be relevant. We conclude that *only if* pulsar B's spin is actually linked to the torque induced by the physical mechanism producing the kick it must be offset from the center of mass of the collapsing neutron star progenitor.

Regardless of the specifics of the collapse process, however, the expected alignment of the spin of pulsar B's SN progenitor with the pre-SN orbital angular momentum and the observed misalignment of pulsar B's spin and orbit at present uniquely imply that pulsar B's spin is dominated by angular momentum produced during the SN process, not angular momentum provided by the progenitor. The realization of this empirical constraint on angular momentum production in supernovae presented here is uniquely enabled by the spin spin misalignment in the PSR J0737-3039 system (Lyne et al. 2004; Ferdman et al. 2008; Lyutikov & Thompson 2005) and can be used to guide core-collapse simulations and the quest for the understanding of compact object spins and kicks.

We thank Tsing Wai Wong for providing data on the distribution of allowed pulsar kicks from the current orbital constraints from Wong et al. (2010) (Figure 5). We also thank Ingrid Stairs, Hans-Thomas Janka, Adam Burrows, and Rodrigo Fernandez for helpful comments on drafts of this manuscript. WMF and VK are partially supported by NSF grant AST-0908930. KK acknowledges support from a NASA summer research grant through the Illinois Space Grant NNG05G381H. ML is supported by NASA grant NNX09AH37G.

REFERENCES

Blondin, J. M., & Mezzacappa, A. 2007, Nature, 445, 58, arXiv:astro-ph/0611680

Breton, R. P. et al. 2008, Science, 321, 104, arXiv:0807.2644

Burgay, M. et al. 2003, Nature, 426, 531

Dessart, L., Burrows, A., Ott, C. D., Livne, E., Yoon, S., & Langer, N. 2006, ApJ, 644, 1063, arXiv:astro-ph/0601603

Dewi, J. D. M., & van den Heuvel, E. P. J. 2004, MNRAS, 349, 169, arXiv:astro-ph/0312152

Ferdman, R. D. et al. 2008, in American Institute of Physics Conference Series, Vol. 983, 40 Years of Pulsars: Millisecond Pulsars, Magnetars and More, ed. C. Bassa, Z. Wang, A. Cumming, & V. M. Kaspi, 474–478, arXiv:0711.4927

Janka, H., Marek, A., Müller, B., & Scheck, L. 2008, in American Institute of Physics Conference Series, Vol. 983, 40 Years of Pulsars: Millisecond Pulsars, Magnetars and More, ed. C. Bassa, Z. Wang, A. Cumming, & V. M. Kaspi, 369–378, arXiv:0712.3070

Kitaura, F. S., Janka, H., & Hillebrandt, W. 2006, A&A, 450, 345, arXiv:astro-ph/0512065

Lorimer, D. R. et al. 2007, MNRAS, 379, 1217, arXiv:0705.3269

Lyne, A. G. et al. 2004, Science, 303, 1153

Lyutikov, M., & Thompson, C. 2005, ApJ, 634, 1223, arXiv:astro-ph/0502333

Miyaji, S., Nomoto, K., Yokoi, K., & Sugimoto, D. 1980, PASJ, 32, 303

Nomoto, K. 1984, ApJ, 277, 791

——. 1987, ApJ, 322, 206

Piran, T., & Shaviv, N. J. 2005, Phys. Rev. Lett., 94, 051102, arXiv:astro-ph/0409651

Podsiadlowski, P., Dewi, J. D. M., Lesaffre, P., Miller, J. C., Newton, W. G., & Stone, J. R. 2005, MNRAS, 361, 1243, arXiv:astro-ph/0506566

Podsiadlowski, P., Langer, N., Poelarends, A. J. T., Rappaport, S., Heger, A., & Pfahl, E. 2004, ApJ, 612, 1044, arXiv:astro-ph/0309588

Rantsiou, E., Burrows, A., Nordhaus, J., & Almgren, A. 2011, ApJ, 732, 57, arXiv:1010.5238

Spruit, H., & Phinney, E. S. 1998, Nature, 393, 139, arXiv:astro-ph/9803201

Stairs, I. H., Thorsett, S. E., Dewey, R. J., Kramer, M., & McPhee, C. A. 2006, MNRAS, 373, L50, arXiv:astro-ph/0609416

Tauris, T. M., & van den Heuvel, E. P. J. 2006, Formation and evolution of compact stellar X-ray sources, ed. Lewin, W. H. G. & van der Klis, M., 623–665

van den Heuvel, E. P. J. 2004, in ESA Special Publication, Vol. 552, 5th INTEGRAL Workshop on the INTEGRAL Universe, ed. V. Schoenfelder, G. Lichti, & C. Winkler, 185–+, arXiv:astro-ph/0407451

van den Heuvel, E. P. J. 2007, in American Institute of Physics Conference Series, Vol. 924, The Multicolored Landscape of Compact Objects and Their Explosive Origins, ed. T. di Salvo, G. L. Israel, L. Piersant, L. Burderi, G. Matt, A. Tornambe, & M. T. Menna, 598–606, arXiv:0704.1215

Wang, C., Lai, D., & Han, J. L. 2006, ApJ, 639, 1007, arXiv:astro-ph/0509484

Willems, B., & Kalogera, V. 2004, ApJ, 603, L101, arXiv:astro-ph/0312426

Willems, B., Kaplan, J., Fragos, T., Kalogera, V., & Belczynski, K. 2006, Phys. Rev. D, 74, 043003, arXiv:astro-ph/0602024

Wong, T., Willems, B., & Kalogera, V. 2010, ApJ, 721, 1689, arXiv:1008.2397

Wongwathanarat, A., Janka, H., & Müller, E. 2010, ApJ, 725, L106, arXiv:1010.0167

This preprint was prepared with the AAS LaTeX macros v5.2.